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An HF Communications Frequency-Management Procedure for Forecasting the Frequency of Optimum Transmission

M. DAEHLER

Ionospheric Effects Branch
Space Science Division
E. O. Hulburt Center for Space Research

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This report describes a procedure for forecasting the Frequency of Optimum Transmission (FOT) on a high-frequency communications path when the Maximum Observable Frequency (MOF) on another path and an historical record of the correlations of MOFs measured on the two paths are known. The procedure, known as "Updating," uses MOF values measured by an oblique-incidence sounder on one path to adjust the MOF forecast by the MINIMUF model for a second path. The model is Updated by using one of its input parameters, the solar 10.7 cm flux, as an adjustable parameter to make the predicted MOF equal the measured MOF on the sounded path. The measurement of the correlation coefficient connecting MOFs measured on a pair of sounded paths is discussed. After forecasting the MOF, statistical methods are used to determine the FOT, which may be defined as the highest frequency not exceeded by the MOF ninety percent of the time. Data from the 1980 Solid Shield series of ionospheric measurements are used in examples of correlation coefficient measurements, Updated forecasts, and FOT determinations.

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AN HF COMMUNICATIONS FREQUENCY-MANAGEMENT PROCEDURE FOR FORECASTING THE FREQUENCY OF OPTIMUM TRANSMISSION

1. INTRODUCTION

The needs to utilize the crowded HF channels efficiently and to maintain a high degree of communications channel connectivity justify a substantial effort to accurately predict the values of those ionospheric parameters from which optimum frequencies may be selected. Oblique incidence sounders operating over all necessary communications paths would give a near-ideal amount of the information required for optimum frequency management. In particular, they give the Maximum Observable Frequency (MOF) with an rms error on the order of 1 Mhz, they give relative amplitude as a function of frequency, and they give information on multimoding. But the procurement and operation of that many sounders would be unrealistically expensive; sounders cannot forecast future values of the MOF, and there are problems associated with their use in denied areas and in covert situations. Vertical incidence sounders have similar advantages and disadvantages. As a consequence, ionospheric models based on extensive periods of ionospheric measurements are routinely used, and will probably continue to be used for a long time to come, to predict the parameters required for HF frequency selection. One of the most successful of these is the MINIMUF model developed by the Naval Ocean Systems Center (NOSC). This prediction algorithm requires only very modest computing facilities and is thus suitable for field use. Using only a current (within 1-5 days) value of the solar 10.7 cm ionizing flux, MINIMUF is capable of predicting the MOF over any desired paths with an rms accuracy of 3-5 Mhz. Other models, such as IONCAP, are slightly more accurate but require much more extensive computing facilities and are thus not easily field-usable. None of the models, however, gives forecasts with an accuracy approaching that of the sounder measurements. This leads us to attempt an improvement in forecasting accuracy by combining sounder measurements with predictive modelling. With sounder data from a small number of sounders used as input, the models can then produce predictions for a much larger number of communications paths. The goal is to produce predictions with an accuracy approaching that of sounder measurements and with convenience approaching that of model calculations. This is the basis of the NRL "Updating" technique. It is the purpose of this technical note to investigate the foundations of the Updating technique and to derive one of its numerous possible applications: a procedure for using the MOF measured on a sounded path to forecast the highest frequency on an unsounded path which, with a specified degree of probability, will not exceed the MOF on that path. This frequency is called the frequency of optimum transmission, or FOT.

To illustrate these techniques, data taken from the Solid Shield experiment, a test of HF communication procedures in the Eastern United States, were used. These data were selected because they covered a relatively long time interval (17 days) and were available in a readily usable form.

Work on Updating procedures of NRL has used data from oblique-incidence sounders. Only 1-hop propagation modes have been considered, so that the MUF values obtained are characteristic of the ionosphere at the midpoints of the paths. Similarly, the correlation of properties on the two sounded paths actually measures the correlation of ionospheric properties at the midpoints of the two paths. These conditions differ from the conditions present in

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other investigations referenced in this report, in which only vertical-incidence sounder data were used.

The correlation of ionospheric properties on two paths separated in time and/or space must be made through a model which incorporates the temporal and spatial MOF dependence and which can be adjusted by a time-and-space invariant parameter. In the present work the MINIMUF model is used exclusively because of its simplicity and relative accuracy. The model is adjusted by a single parameter, the 10.7 cm solar flux.

Section II of this report contains a definition and examples of the correlation coefficient connecting the modelling parameters measured on a pair of paths, and discusses how the correlation coefficient depends on the time of day.

In Section III three examples of forecasting are discussed. In the first case, MINIMUF is used alone to forecast the MUF. In the other cases the MINIMUF prediction of MOF on a specified path is modified by using MOF values measured, respectively, on the same or a different path. The quality of the forecasts is measured by comparing the rms differences of the forecast and measured values.

In Section IV it is shown how to forecast, for an unsounded path, the Frequency of Optimum Transmission - that is, the highest frequency which is assured, with a specified probability, to be below the MOF on that path, when the MOF on a sounded path and the correlation of the modelling parameter for the two paths are known.

II. MOF CORRELATION

Correlation Parameter

While the MOF is considered the single most useful ionospheric property for frequency management purposes, one cannot directly correlate MOFs at different positions on the earth because of the MOF's well-known dependence on latitude and time of day (Rush 1976). Instead, we adopt a MOF-prediction model which incorporates the effects of geographical positon and time of day, and look for some parameter which can be adjusted to make the predicted MOF equal the real (i.e., measured) MOF. The MINIMUF model (Rose et al 1978a,b) was chosen because it is easy to use, reasonably accurate, and has enjoyed considerable success in frequency-management operations. MINIMUF computes the MOFs by the equation

$$MOF = (1 + R/250)\, M \sqrt{A_0 + A_1 (\cos \chi_{eff})^{\frac{1}{2}}},$$

where R = sunspot number, A_0 and A_1 are constants, χ_{eff} is the effective zenith angle, and M is a function of pathlength and ionospheric layer structure. The MINIMUF sunspot number R is obtained from the values of solar 10.7 cm flux F_0 broadcast by WWV according to the formula

$$R = 561.8 \left\{[(0.52998 - 0.000356\,(63.75 - F_0))] - 0.728\right\}$$

The sunspot number so calculated is nearly directly proprotional to the 10.7 cm flux F_0. Following recent custom, we use the 10.7 cm flux parameter as the adjustable parameter which is used to force MINIMUF to give the measured MOF value. This <u>effective 10.7 cm flux</u>, which we shall call simply the "effective flux", is usually different from direct measurements of the 10.7 cm flux, and therefore loses its literal meaning. It can nevertheless be considered as an "adjusted 10.7 cm flux" which is (in principle) independent

of geographical position and therefore suitable as a parameter with which the correlation of ionospheric properties may be tested.

This technique of correlating an adjustable model parameter is somewhat different from previous methods in which differences between model values and measured values of MUF were correlated (Rush 1976; Gautier and Zacharisen 1965; Beckwith and Kao 1975).

Correlation of Effective Fluxes on a Pair of Paths

To illustrate the correlation of effective fluxes for a pair of paths we use data from the Solid Shield experiment (Uffelman and Harnish 1982), a test of HF communications procedures which occurred on 3-20 May 1981. These data were chosen because of the relatively large quantity of data available: there are 1604 MOF measurements, covering 401 hours of sounder operation spread over 17 days. MOFs were measured on the six paths listed in Table 1 and illustrated in Figure 1.

Figure 2 shows a comparison of the effective fluxes measured for the MacDill-Norfolk and Lejeune-Norfolk paths. Each of the three plots includes data acquired during a specific hour of each of a number of days. In Figure 2a, for example, the nine data points refer to data acquired between 0700 and 0800Z on each of nine days. Since ionograms were made every fifteen minutes, each effective flux value plotted is the flux for which MINIMUF produces MUF values closest to the measured values for the four measurements of the hour, in the sense of smallest rms difference. Effective fluxes were calculated with the NRL OISI computer program. Figures 2a, 2b, and 2c were chosen to illustrate situations in which the correlation is, respectively, about average, a little better than in most, and worse than in most situations.

For each of the plots in Figure 2 a linear regression line in the form

$$Y = a + b X \tag{1}$$

was calculated, where X and Y measure the effective fluxes on the Lejeune-Norfolk and MacDill-Norfolk paths, respectively. The fitted line may be used with MINIMUF for forecasting, since a measured MOF and the derived effective flux on the Lejeune-Norfolk path lead, through equation 1, to an effective flux and then to a MINIMUF MOF prediction on the MacDill-Norfolk path. This technique of using a model and a MOF measurement on one path to forecast a MOF on another path has been termed "Updating" and has been the subject of a number of NRL studies (Uffelman 1981; Uffelman et al 1981, 1982, 1984a, 1984b). We note that the use of equation 1 to forecast the effective flux on an unmeasured path represents a departure from previous applications of Updating, where the simpler relation Y = X was used. In principle, Y could be calculated as a polynomial in X of arbitrarily high degree, but the presently-available accuracy of MOF and effective-flux measurements doesn't justify the higher precision.

In some correlation plots it was noticed that one or two "wild" points resulted in a linear regression line with a slope differing greatly from the expected slope of $\sim 45^{o}$, as illustrated in Figure 3. While one must be cautious about throwing out data, occasional events such as violent ionospheric disturbances, temporary electrical disturbances, or blunders in measurement can sometimes obscure a real correlation. Therefore, we have in some cases processed the data twice, first using all the data, and then eliminating by subjective exclusion up to three points per plot. Not surprisingly, the exclusion process can greatly improve the correlation plot, as illustrated in Figure 3. With a larger data base this procedure would presumably become unnecessary.

The correlation of effective fluxes on a pair of paths can be measured quantitatively by the correlation coefficient r. Let $X_1, X_2, \ldots X_r$ be n values of effective flux over path 1 at the times $t_1, t_2, \ldots t_n$. Let $Y_1, Y_2, \ldots Y_n$ be the values of effective flux over path 2 at the same times. The correlation of the effective fluxes on the two paths is defined by the correlation coefficient r:

$$r = \frac{n \sum_{i=1}^{n} X_i Y_i - \left(\sum_{i=1}^{n} X_i\right)\left(\sum_{i=1}^{n} Y_i\right)}{\sqrt{n \sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}\sqrt{n \sum_{i=1}^{n} Y_i^2 - \left(\sum_{i=1}^{n} Y_i\right)^2}}$$

(See, for example, Ref. 8, p. 523).

Thus defined, the correlation coefficient measures the degree of linear relationship between the variables X and Y and is independent of the units in which the variables are measured. It can vary between r=1 (perfect correlation) to -1 (perfect anti-correlation). When applied to forecasting, r=1 implies forecasting with near-certainty, and r=o implies uselessness. A negative correlation coefficient is inconsistent with our premises; it is considered a non-physical result and therefore in error.

The significance of the correlation coefficient must be measured in terms of its ability to forecast the value of effective flux on one path when the effective flux on the other path has been measured. To make such inferences, one must assume that variables X and Y are both normally distributed. Such an assumption seems reasonable, though we don't verify that here. A useful interpretation is that

$$r^2 = \frac{\text{Variation in Y explained by regression line.}}{\text{Total variation observed in Y.}}$$

The quantity r^2 is known as the coefficient of determination. Thus correlation coefficients on the order of 0.9 or greater imply $r^2 \gtrsim 0.8$, which indicates that the assumption of linear relationship between the effective fluxes is reasonably valid.

Time Variation of Correlation Coefficient

We have computed the correlation coefficient as a function of time for eighteen combinations of the six paths involved in the Solid Shield project. The results are shown in Figure 4. For most pairs of paths there are two plots: one uses all the data, and the other uses data from which "wild points" have been discarded. We make the following observations:

1. There are many measurements of correlation coefficients between 0.9 and 1, corresponding to coefficients of determination between 0.8 and 1, which implies a reasonable likelihood of using the correlation of effective fluxes as a predictive tool;

2. In some cases, however (such as in the Lejeune-Driver, Driver-Norfolk correlation, plot 2), the improvement in correlation caused by subjectively eliminating "wild points" is striking. The eliminated data in this situation were a string of consecutive data points on a single day, probably indicating a systematic error in measuring the MUF on one of the paths during that day.

3. Seven of the diurnal correlation plots (Figure 4, plots 1, 8-13) indicate a large decrease in the correlation coefficient during a period of four hours centered on approximately 1600 UT. Since all involve the MacDill-Norfolk path, the cause is probably some systematic error in those data.

4. Aside from the gross features mentioned above, the correlation coefficient tends to be at its highest around midnight UT (1900 LT) and tends to be somewhat decreased around 1400 UT and possibly around 0500 UT (0900 and 1200 LT, respectively). These trends are not well defined, however.

Diurnal Variation of Regression Coefficients

Figure 5 shows the diurnal variation of the constants A and B determined for the linear regression fit to the effective fluxes calculated for the Lejeune-Norfolk, Driver-Bragg pair of paths. The hand-drawn lines show that the coefficients may possibly be described as varying roughly sinusoidally, with a twelve-hour period. Such a regularity would tend to indicate a deficiency in MINIMUF's ability to account for geographical MUF dependence, at least as far as this particular example is concerned.

Similar plots for several other pairs of paths were made to see if the regularity observed for the Lejeune-Norfolk, Driver-Bragg regression coefficients is typical. The results, shown in Figure 6, are ambiguous. From these data, one can only conclude that in some instances a periodic variation in regression coefficients occurs, and that a model improvement should be possible.

Spatial De-correlation

It is reasonable to expect the correlation of effective fluxes determined for a pair of paths to decrease as the distance between the path centers (called control points) increases. To test this effect, the average correlation coefficient for each of the eighteen pairs of paths used in creating Figure 4 is plotted as a function of separation of the control points (Figure 7). As expected, the correlation decreases with increasing control-point separation. At longer path separations the scatter in the correlation coefficient becomes large. Because of the limited scope of the Solid Shield test (there are no control-point separations greater than 700 km), it is not possible to confirm the decrease in f_0F_2 correlation measured by Rush (1976) for ionospheric position separations up to 5000 km.

III. MUF FORECASTS

We consider three ways to forecast the MUF, all of them using MINIMUF:

1. MINIMUF alone
2. MINIMUF updated by sounder measurements on the same path
3. MINIMUF updated by sounder measurements on a different path.

Forecasting by MINIMUF Alone

Given a specified communications path, day of year, and solar 10.7 cm flux value, the MINIMUF model predicts the MUF as a funcion of time of day. There is some debate about the most appropriate value of solar flux to use; in some cases the daily value (as broadcast hourly by WWV) seems to work well, while in other cases a value equal to the flux averaged over the previous five days is preferred. To continue with the previously-discussed example from the Solid Shield test (Lejeune-Norfolk path, 3-19 May 1981), we have calculated the MINIMUF MUF predictions and compared them with the observed MUFs. These data include approximately 350 hours of measurements spanning a period of

seventeen days. The rms error of these forecasts turned out to be 2.49 MHz when the daily solar flux value was used, and 2.64 MHz when the five-day average was used.

These values are included in Figure 8, which shows the rms difference between the forecast and measured MOF values as a function of the time delay between the time of forecast and the time of measurement. Since the MINIMUF forecast changes only once per day, when a new solar flux value becomes available, the rms error is independent of the delay between the times of forecasting and measurement, for times up to twenty-four hours. Thus, the MINIMUF-alone rms error appears as a horizontal line in Figure 8.

Forecasting by the Updated MINIMUF Model

The prospect of improving forecasting accuracy by "Updating" is based on the presumption of low-frequency ($f \lesssim 1$ day $^{-1}$) variations in the MOF which are not accounted for in the MINIMUF model. If the model MOF forecast is multiplied by a constant which makes the result agree perfectly with a current measured MOF, it is reasonable to expect that multiplying the model forecast for a later time by the same constant will improve the forecast. Since the solar 10.7 cm flux enters into the MINIMUF calculations essentially as a multiplicative factor, it has been convenient to modify the model's predictions by using an "effective flux" instead of the actual one. The effective flux is determined at the time of Updating and is used to obtain MINIMUF forecasts until a new effective flux is determined. The purpose of this section is to show an example of Updating methods and to show how its efficacy in improving MOF forecasting can be measured.

The effective flux may be determined from sounder measurements, such as the ionograms from the oblique-incidence sounders used in the Solid Shield test. Effective flux measurements may be made either on the path for which forecasts are desired or on some other path. When using an effective flux measured on a path different from the path on which the forecast is desired, it is necessary to use a correlation function similar to those illustrated in Figure 2 to determine the effective flux on the path for which predictions are being made.

Figure 8 shows the rms error between forecast and measured MOFs on the Lejeune-Norfolk path as a function of the time delay between forecast and measurement. One curve results from predictions using effective flux measurements from the same path. The calculations for this curve include all data for that path for which both forecast and measurement (within 24 hours) were possible. In this case, the correlation measurements are not involved. The other two curves are derived from forecasts based on effective fluxes measured on two other paths: Driver-Ft. Bragg, and MacDill-Ft. Bragg. In these cases, the corresponding effective fluxes for the Lejeune-Norfolk path were determined from correlation plots of the type illustrated in Figure 2. The presentation of data in Figure 8 and conclusion based on the figure are flawed by the fact that the MOF measurements used to check the forecasts were also included in the data used to determine the correlation coefficients. With a larger data base, it would be possible to avoid this difficulty. Figure 8 is included, however, because it typifies the data required to determine the efficacy of Updating techniques.

Comments on Updating Techniques

The following observations can be made on the previous example of Updating procedures:

1. For the Lejeune-Norfolk data presented in Figure 8, the Updated-MINIMUF forecasts for delay times up to about six hours result in a smaller rms error than forecasts using MINIMUF alone.

2. For prediction times between twelve and eighteen hours, Figure 8 shows the somewhat surprising result that the Updated-MINIMUF forecasts are inferior to those using MINIMUF alone.

3. There is a marked similarity in the Updated-MINIMUF results for the three ways of determining the effective flux on the Lejeune-Norfolk path. It seems surprising that, except for short delay times (1-6 hours) between forecast and observation, the forecasts based on Lejeune-Norfolk measurements are inferior to those based on measurements from the other paths.

4. The MINIMUF-alone rms error of $\sim$2.6 MHz are substantially lower than the generally-applicable 3.5 MHz errors claimed by MINIMUF. It is possible that the Lejeune-Norfolk path is a relatively favorable case for the application of MINIMUF prediction.

5. There is a trend for forecasts for $\sim$ 12 hours ahead to be worse than those for $\sim$ 24 hours ahead, regardless of the type of Updating. This is probably inherent in the model; use of a more sophisticated model might eliminate this effect.

6. It should be noted that the results presented in this report are based on a very small data sample and may not represent general ionospheric conditions. However, the procedures used are those which may be used to assess the validity of Updating (or other) techniques of MOF forecasting.

7. The dependence of forecast accuracy as a function of time of forecast has not been explored. For example, it may be that forecasts made at sunrise for 12 ahead are better than these made at noon for 12 hours ahead. The Solid Shield data seemed insufficent in quantity for an adequate discussion of this dependence

Although the present work has used a single parameter (the effective flux) measured on a sounded path to update the model forecast of the same parameter on the same path or on an unsounded path, more elaborate schemes are possible. For example, the model forecast of a parameter may be updated using measurements of the same parameter at a number of positions and times, or it may be updated with recent measurements of a number of different parameters (Gautier and Zacharisen 1965, Zacharisen 1965, Zacharisen and Gautier 1964). Updating with a large quantity of sounder data would be appropriate for a network of sounders established for forecasting propagation conditions over a large geographical region.

IV. FREQUENCY MANAGER'S FOT-FORECASTING PROCEDURE

Management of an HF communications network demands the assignment of frequencies in such a way that the requirements of connectivity, data rates, covertness, etc., are achieved. Here we are concerned with only one of the constraints to the assignment process: the requirement that assigned frequencies be at or below the MOF for the assigned communications path. Given a measurement of MOF on a sounded path, we attempt to produce a procedure for determining, with a predetermined probability of success, the highest frequency which does not exceed the MOF on the communications path. Such a frequency may be called the Frequency of Optimum Transmission, or FOT. It is not a single quantity, since it depends on the specified probability. We thus speak, for example, of the "90% FOT" for a given path and time, meaning the highest frequency which, with 90% probability, will be below the actual MOF. This definition differs from that used in some frequency

management procedures, where the MUF is defined as a percentage (typically 85%) of the MOF (Davies 1965). Others simply define the FOT as the 90% FOT defined above (Gautier and Zacharisen 1965).

Probability Interval of an Effective Flux Forecast

In a previous section it was shown how the correlation of effective fluxes on two paths could be approximated by a linear regression line and measured by the coefficient of correlation. Then, in discussing Updating, the measured effective flux on a reference path and the known correlation information were used to forecast the effective flux on a communication path. Here we show the degree of confidence with which this forecast may be used, given a specified amount of correlation data.

We assume that a series of n effective fluxes $X_1, X_2, \ldots X_n$ on one path (called the control path) and the corresponding effective fluxes on $F_1, F_2, \ldots F_n$ on a second path (called the communications path) have been measured and that a linear regression line to approximate the correlation lines has been calculated. Thus, given a subsequent effective flux X measured on the control path, the best estimate of effective flux on the communications path is

$$\hat{F} = a + b X$$

This is not an appropriate effective flux to use for frequency management purposes because there is a 50% probability that the FOT calculated with this effective flux will exceed the actual MUF. Satisfactory communications require a higher probability of success - perhaps 80 to 95%.

The probable error in forecasting an effective flux from the measured correlation relationship may be calculated by appropriate statistical techniques (see Harnett, chapter 10 for a good discussion). For values of control path effective flux near the mean value

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

the standard error of forecast in the corresponding values of F is

$$s_e = \sqrt{\frac{1}{n-2} \sum_{i=1}^{n} (F_i - \hat{F}_i)^2} ,$$

where $\hat{F}_i = a + b X_i$ is the linear regression estimate of F corresponding to the control path effective flux X_i. For values of control path effective flux X not near the mean the standard error of forecast is modified as follows:

$$s_f = s_e \sqrt{1 + \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2}}$$

The quantity under the radical sign quantifies the greater inaccuracy associated with predictions of F for control path effective flux values X far from the mean.

While the linear-regression estimate $\hat{F}$ for the effective flux gives the best prediction possible from the n available measurements, we can also calculate the likelihood that the actual value will depart from the estimated value by a specified amount. Estimates in the present case (i.e., a case in which the standard deviation for all possible values of F is unknown) are expected to follow a t-distribution with $v = n-2$ degrees of freedom. That is, the probability that the actual effective flux will depart from the estimated value $\hat{F}$ by the amount t is given by P (t, v), a function which can be either computed or read from a table. (Most often, the integrals of P over specific ranges of t are tabulated.) The normalized variable t is the effective flux measured in units of the standard error of forecast s_f. Thus a C% confidence interval for the actual flux may be defined by the extremes

$$\hat{F} \pm t_{c,v} s_f,$$

where $t_{c,v}$ is the number for which

$$\int_{-t_{c,v}}^{+t_{c,v}} P\,(t,v)\,dt = C/100$$

Figure 9 illustrates the application of this procedure to the correlation data collected on eleven days in the time interval 0300 -0400 Z on the two Solid Shield paths MacDill-Norfolk and Lejeune-Norfolk. The correlation between the effective flux F on the MacDill-Norfolk path to the effective flux X on the Lejeune-Norfolk path is expressed by the linear regression line

$$\hat{F}\ [\mathrm{MHz}] = 28.88 + 0.831\ X\ [\mathrm{MHz}].$$

The 80, 90 and 95 percent confidence intervals calculated by the above equations are also plotted. Thus, for example, a measured effective flux on the control path (Lejeune-Norfolk) results in a best estimate for the effective flux on the MacDill-Norfolk path of 137.3, with an 80% probability that the actual effective flux will be between 118 and 57 and a 95% probability that it will fall between 106 and 169.

FOT Forecasting Procedure

The MINIMUF program may be used to transform the forecasts of effective flux and confidence intervals on the MacDill-Norfolk path (Figure 9) into FOT forecasts, thereby making the data more readily usable for frequency-management purposes (see Figure 10). In transforming the effective flux forecasts, only the linear regression line and the lower limits of the probability intervals are retained and their labels are changed to correspond to a new interpretation. The new curves represent the most probable value for the MOF, and the frequencies which are expected to be below the actual MOF with probabilities of 90% 95%, and 97.5%. The latter curves are thus labeled as "FOTs" (Frequencies of Optimum Transmission), and the most probable MOF curve is now the "50% FOT". This set of information should be of more assistance in selecting a propagating frequency than a single value of MUF whose relation to the variance in the expected MOF is unknown.

Table 1 — Solid Shield Propagation Paths

TO FT. BRAGG, NC — LATITUDE +35.15 — LONGITUDE -78.98

FROM	LATITUDE	LONGITUDE	DISTANCE (km)	MIDPOINT LAT.	MIDPOINT LONG.
DRIVER, VA	+36.82	-76.50	290	+35.99	-77.75
HURLBERT, FL	+30.3	-86.4	879	+32.78	-82.79
SHAW AFB, SC	+34.97	-80.48	138	+35.06	-79.73
MACDILL AFB, FL	+27.85	-82.48	877	+31.51	-80.80

TO NORFOLK, VA — LATITUDE +36.67 — LONGITUDE -76.23

FROM	LATITUDE	LONGITUDE	DISTANCE (km)	MIDPOINT LAT.	MIDPOINT LONG.
DRIVER, VA	+36.82	-76.50	29	+36.75	-76.36
HURLBERT, FL	+30.3	-86.4	1178	+33.59	-81.50
SHAW AFB, SC	+34.97	-80.48	427	+35.84	-78.38
MACDILL AFB, FL	+27.85	-82.48	1143	+32.30	-79.51
LEJEUNE, NC	+34.67	-77.35	244	+35.67	-76.80

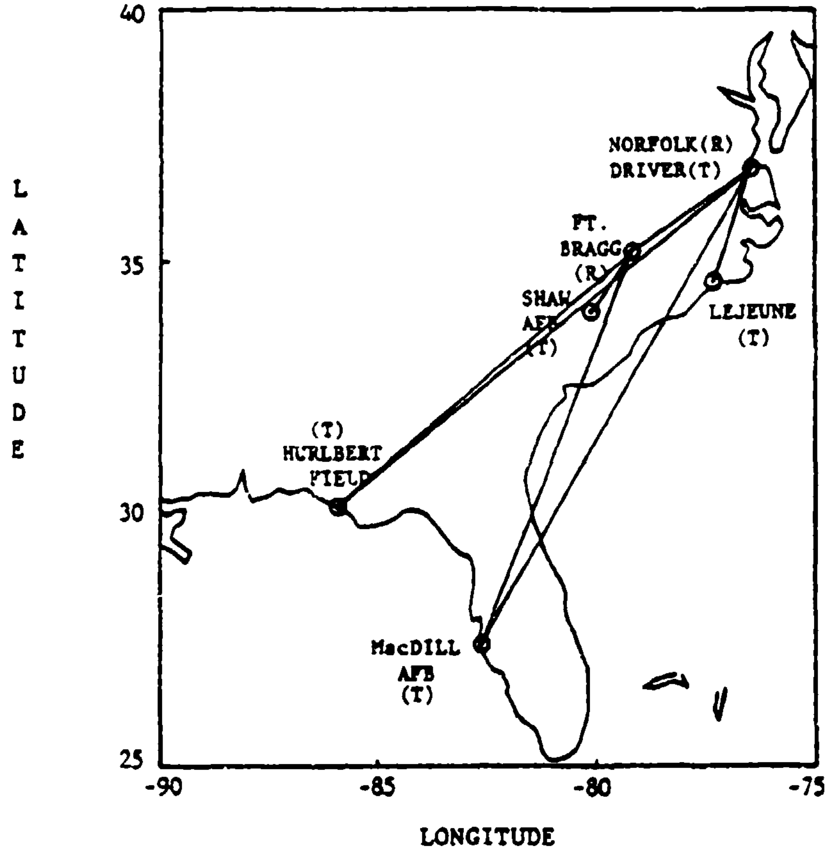

Fig. 1 — Map of southeastern U.S. showing placement of oblique-incidence sounder transmitters (T) and receivers (R) during the Solid Shield program of ionospheric measurements

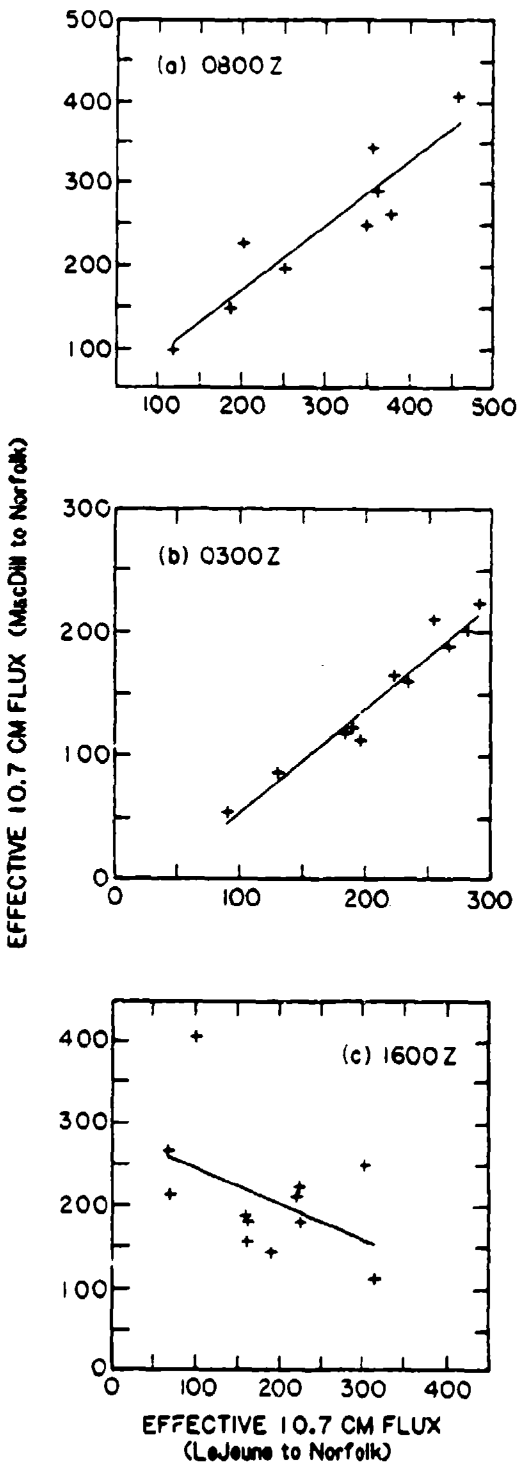

Fig. 2 — Three examples of correlation of effective fluxes on the MacDill-Norfolk and LeJeune-Norfolk paths. An "effective flux" is the 10.7 cm solar flux for which the MINIMUF MUF prediction equals an observed MUF. Examples a, b, and c contain data for the 1-hour intervals starting 0800Z, 0300Z, and 1600Z, respectively, within the Solid Shield test period 8 - 18 May 1981. Straight lines are least-squares regression fits to the data.

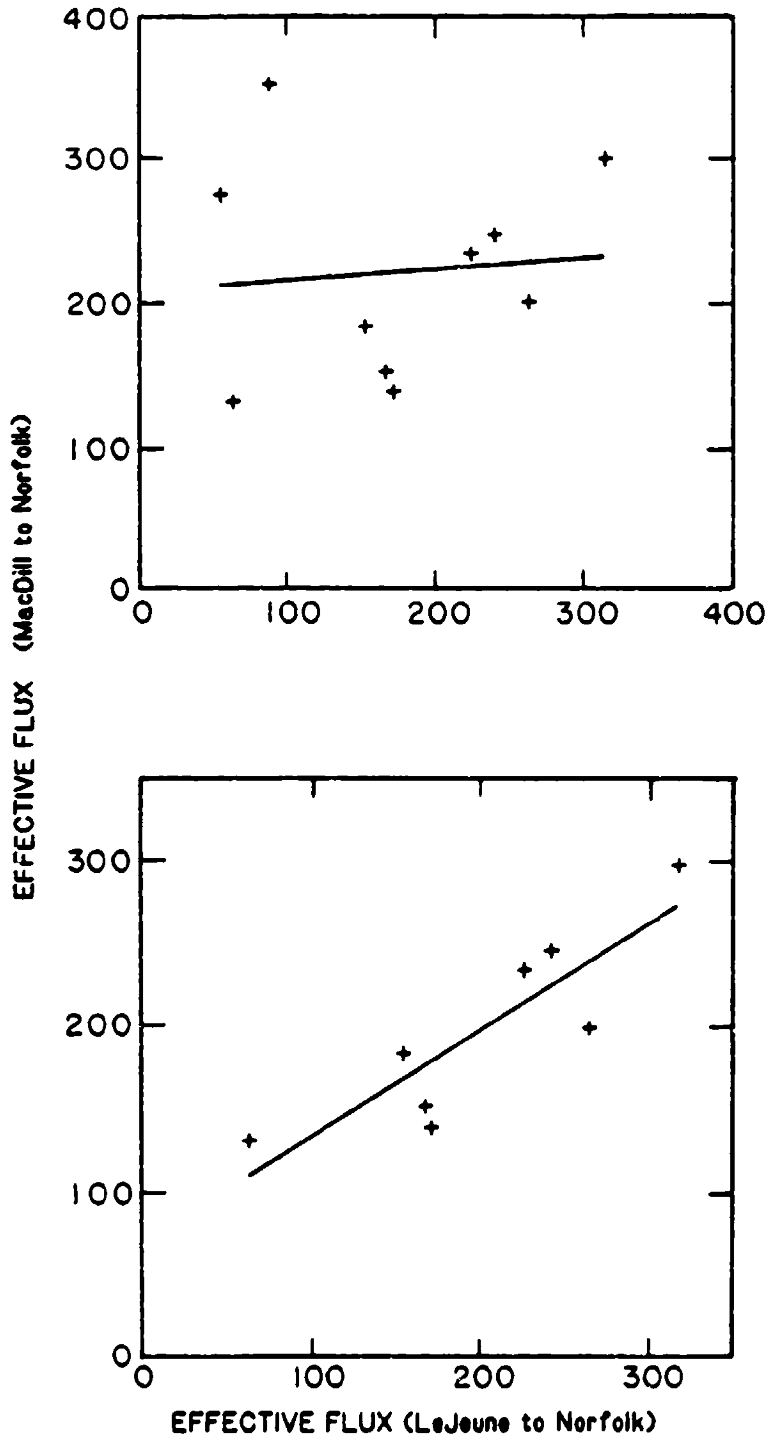

Fig. 3 — Effect of removing "wild points" from the correlation data. Both plots show the correlation of effective fluxes on the MacDill-Norfolk, LeJeune-Norfolk paths for the hour 1500-1600Z. In the lower plot, two "wild points" have been subjectively removed. Straight lines are least-squares regression fits to the data.

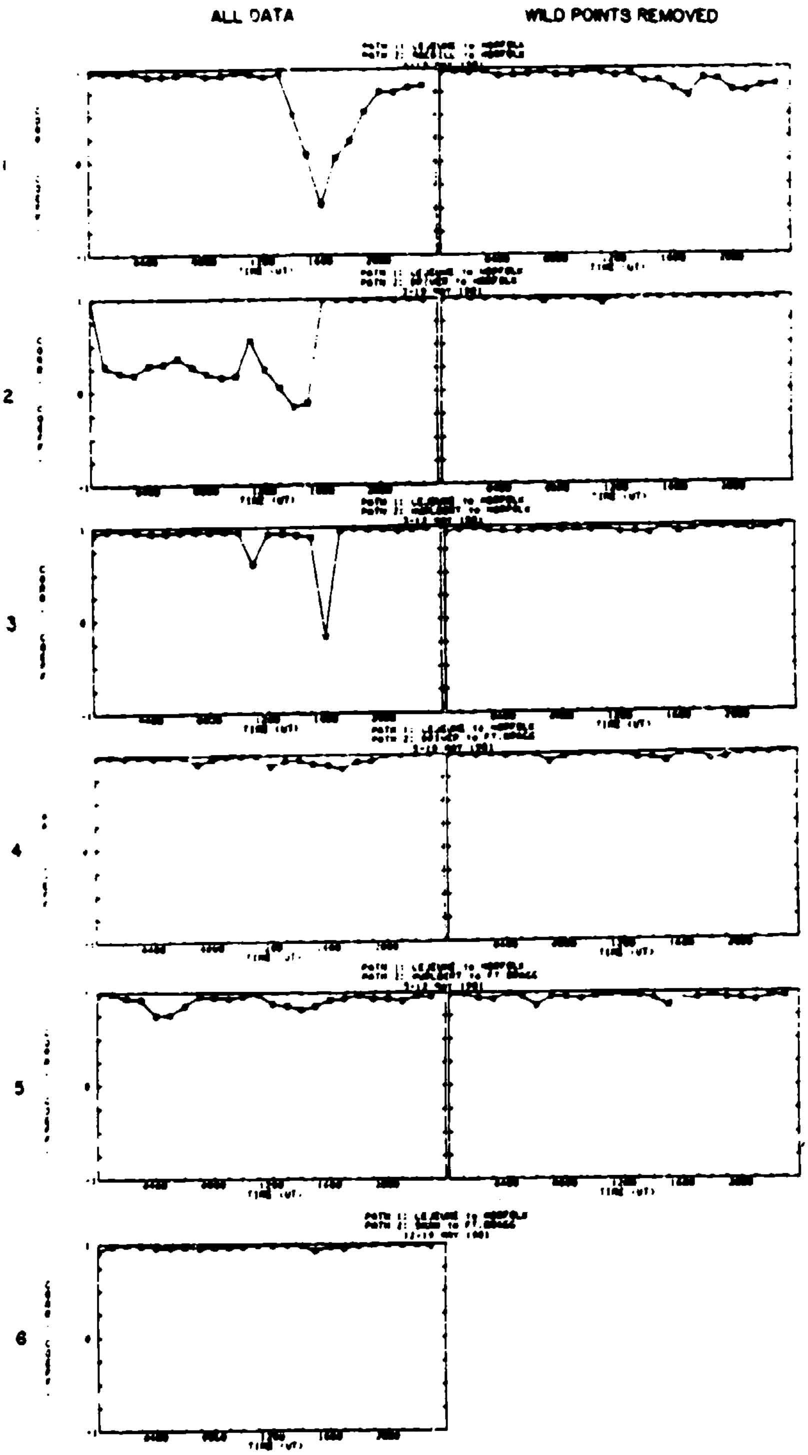

Fig. 4 — Correlation coefficient, as a function of diurnal time, measuring the correlation of effective fluxes for each of eighteen pairs of Solid Shield propagation paths. For each pair, the plot on the left was produced using all the available data; in the plot on the right, some data points were calculated after subjectively deleting "wild points" from the data (see text).

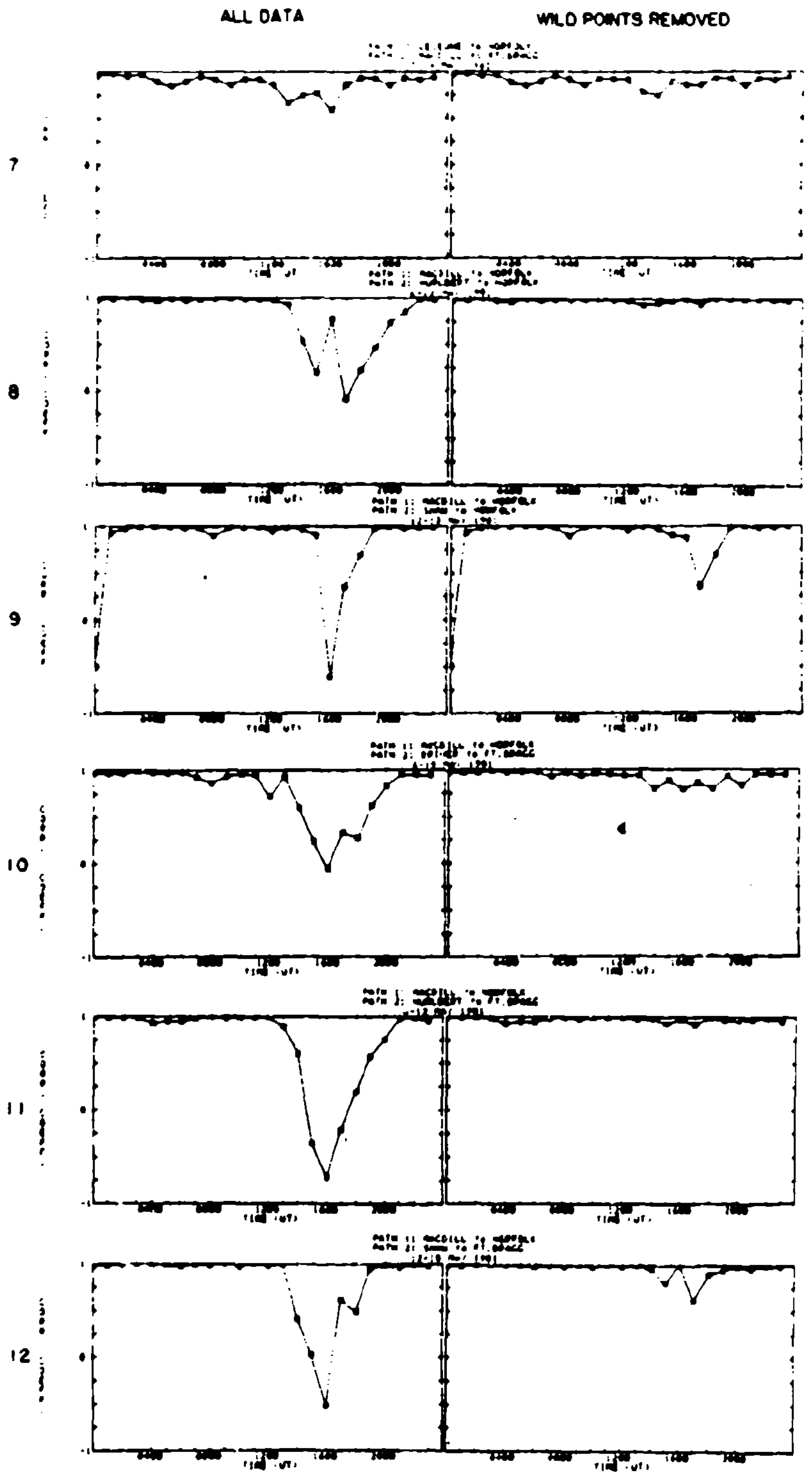

Fig. 4 (Continued) — Correlation coefficient, as a function of diurnal time, measuring the correlation of effective fluxes for each of eighteen pairs of Solid Shield propagation paths. For each pair, the plot on the left was produced using all the available data; in the plot on the right, some data points were calculated after subjectively deleting "wild points" from the data (see text).

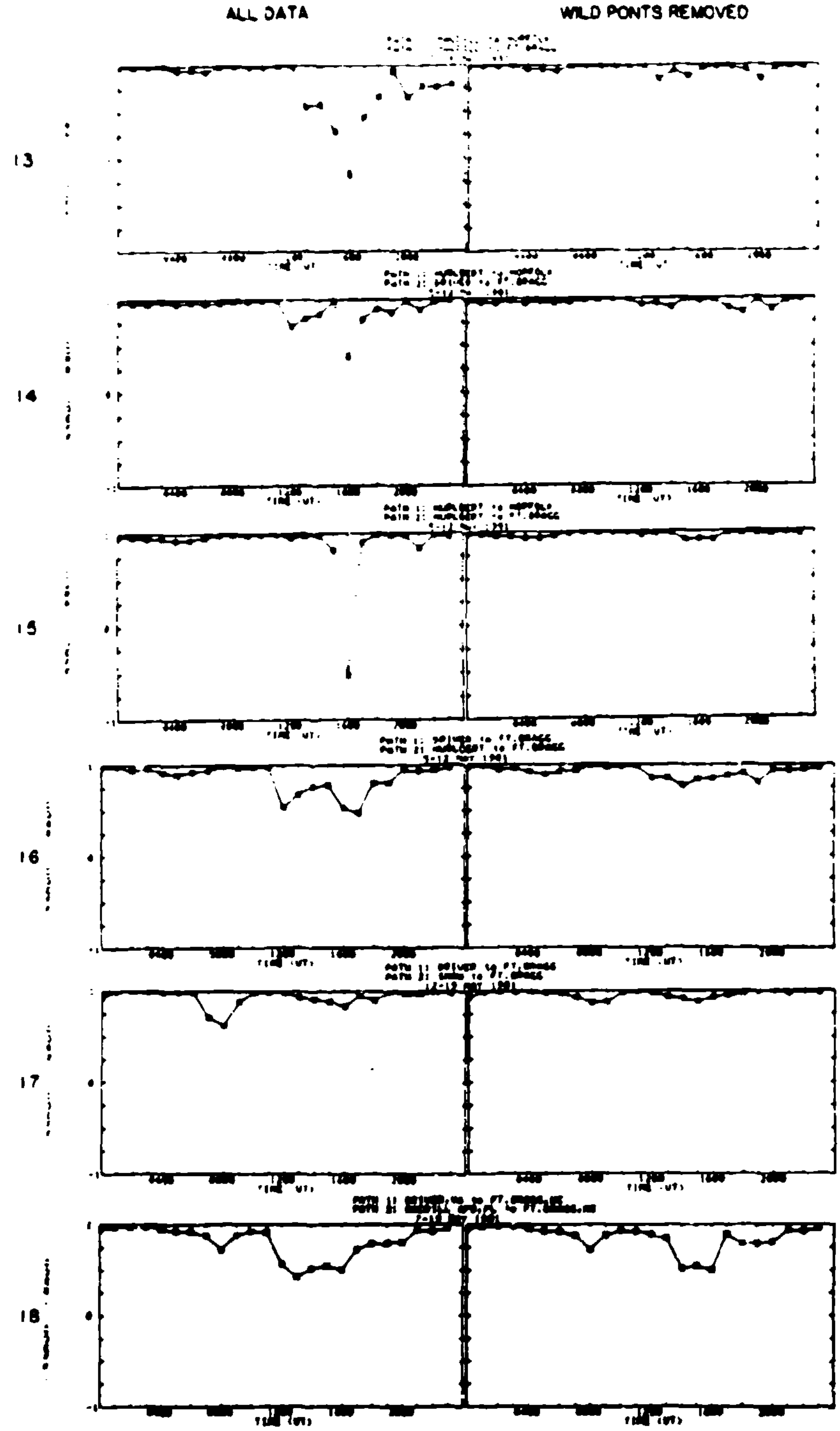

Fig. 4 (Continued) — Correlation coefficient, as a function of diurnal time, measuring the correlation of effective fluxes for each of eighteen pairs of Solid Shield propagation paths. For each pair, the plot on the left was produced using all the available data; in the plot on the right, some data points were calculated after subjectively deleting "wild points" from the data (see text).

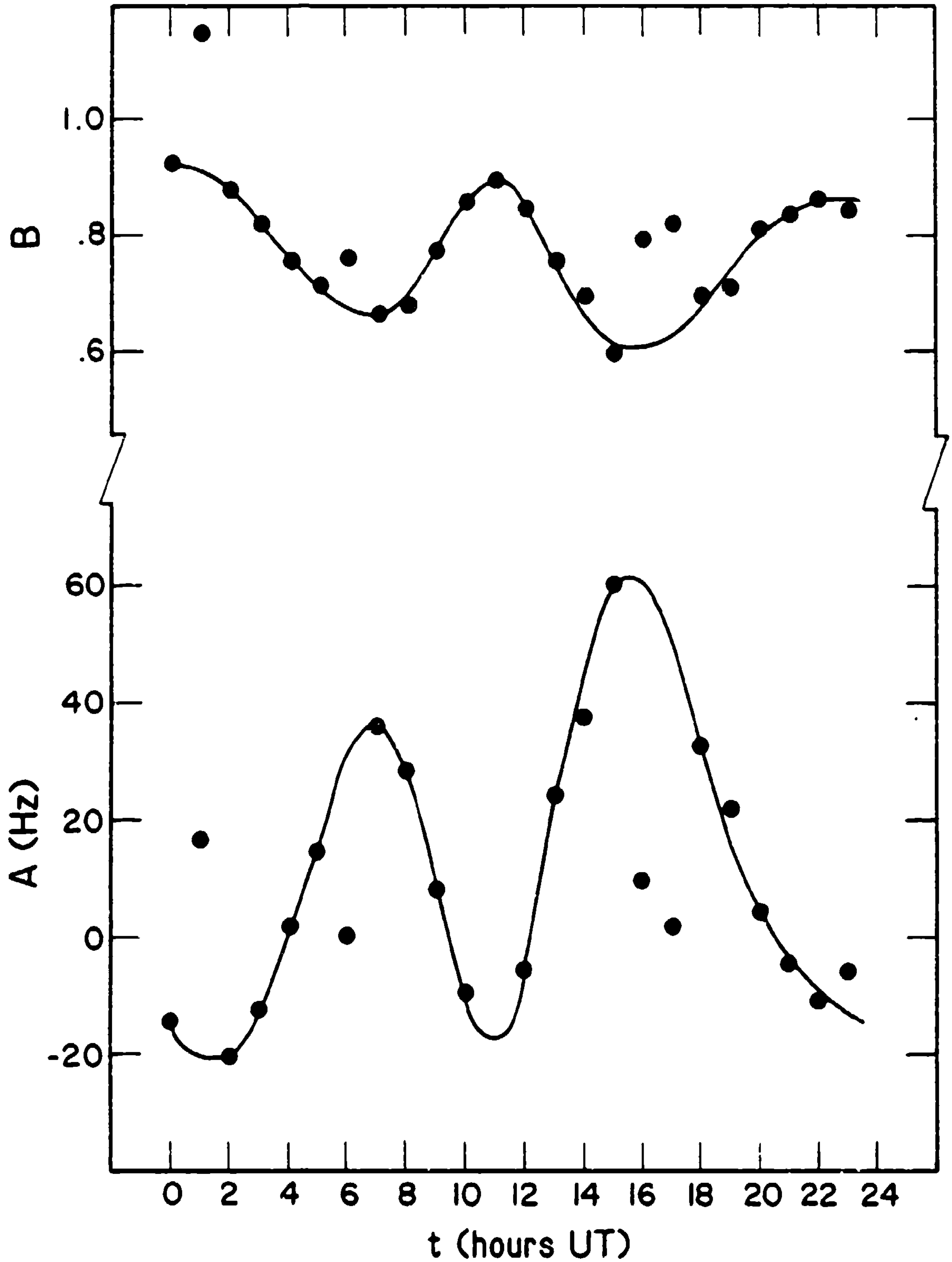

Fig. 5 — Diurnal variation of the linear regression coefficients describing the correlation of effective flux F on the driver to ft. Bragg path with the effective flux X on the Lejeune to Norfolk path. The linear regression lines is $F = A + BX$.

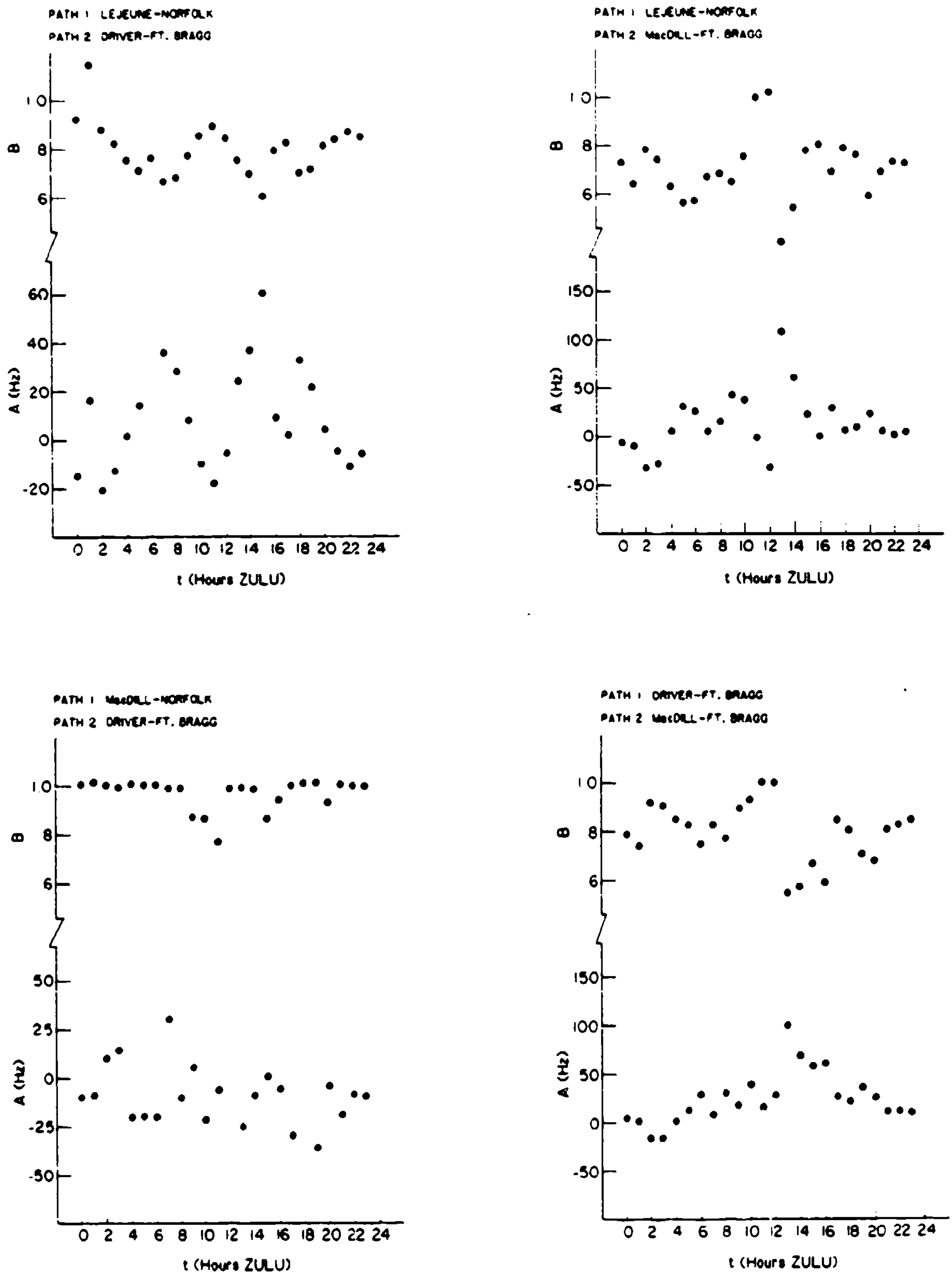

Fig. 6 — Diurnal variations in linear regression coefficients for the correlation of effective fluxes on four pairs of Solid Shield paths.

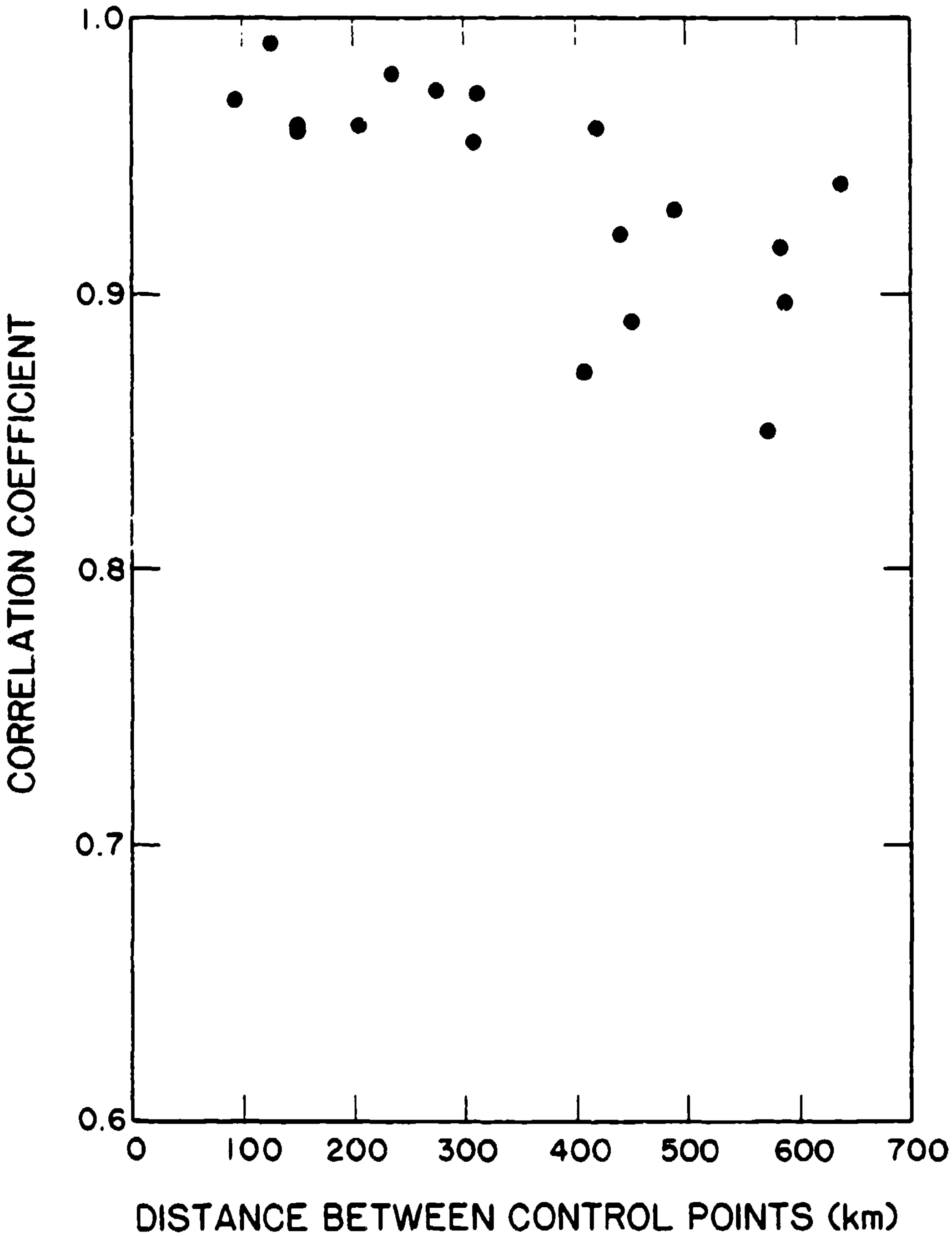

Fig. 7 — Decrease in correlation coefficient with distance between the control points for 18 pairs of Solid shield paths. The control point is the geographical mid-point of a communication path. (It is assumed that all propagation is by single-hop paths.)

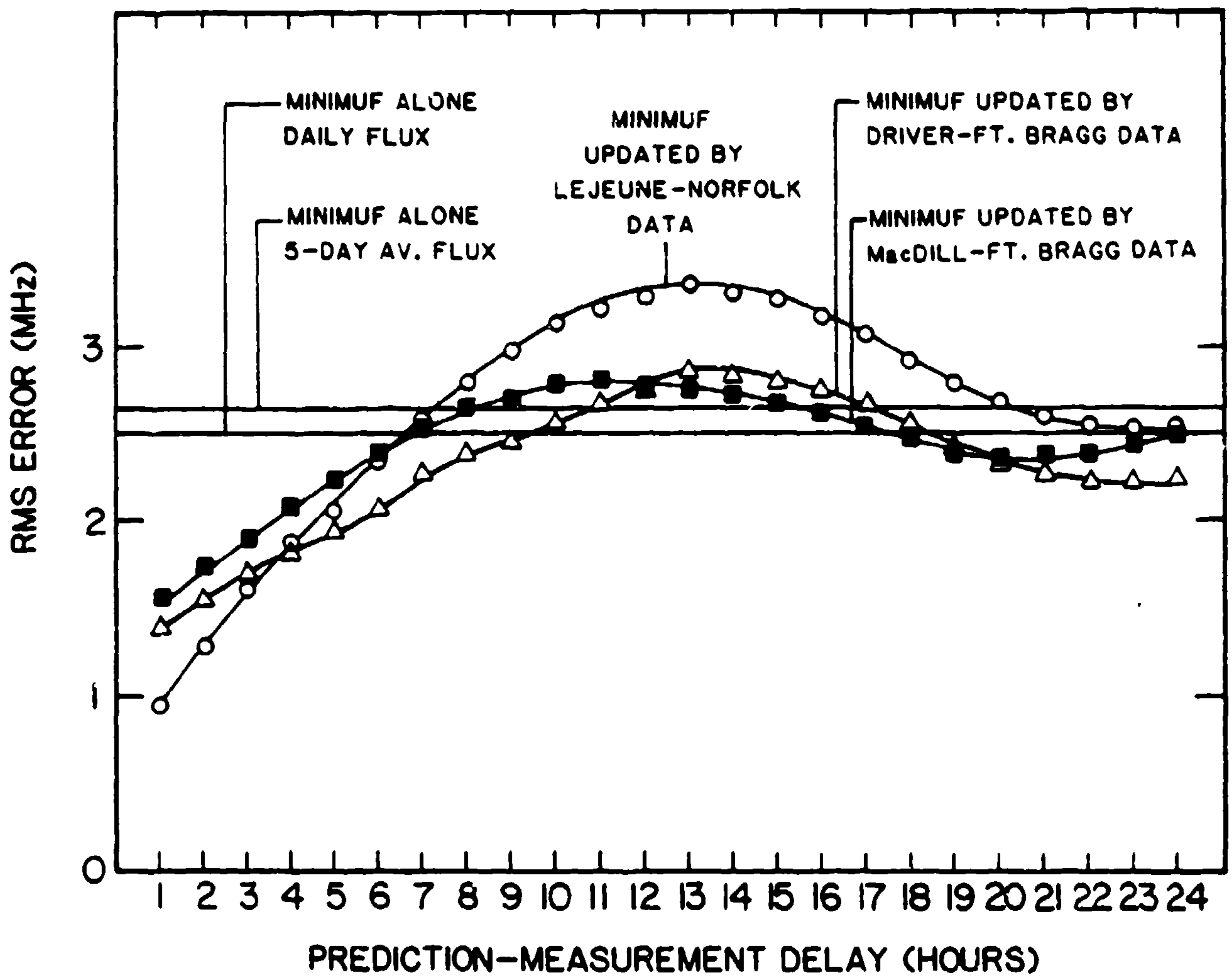

Fig. 8 — RMS error between actual MOFs on the Lejeune to Norfolk path and MOFs predicted by a variety of techniques, as a function of time delay between prediction and measurement. Data include approximately 335 hourly predictions for each value of time delay.

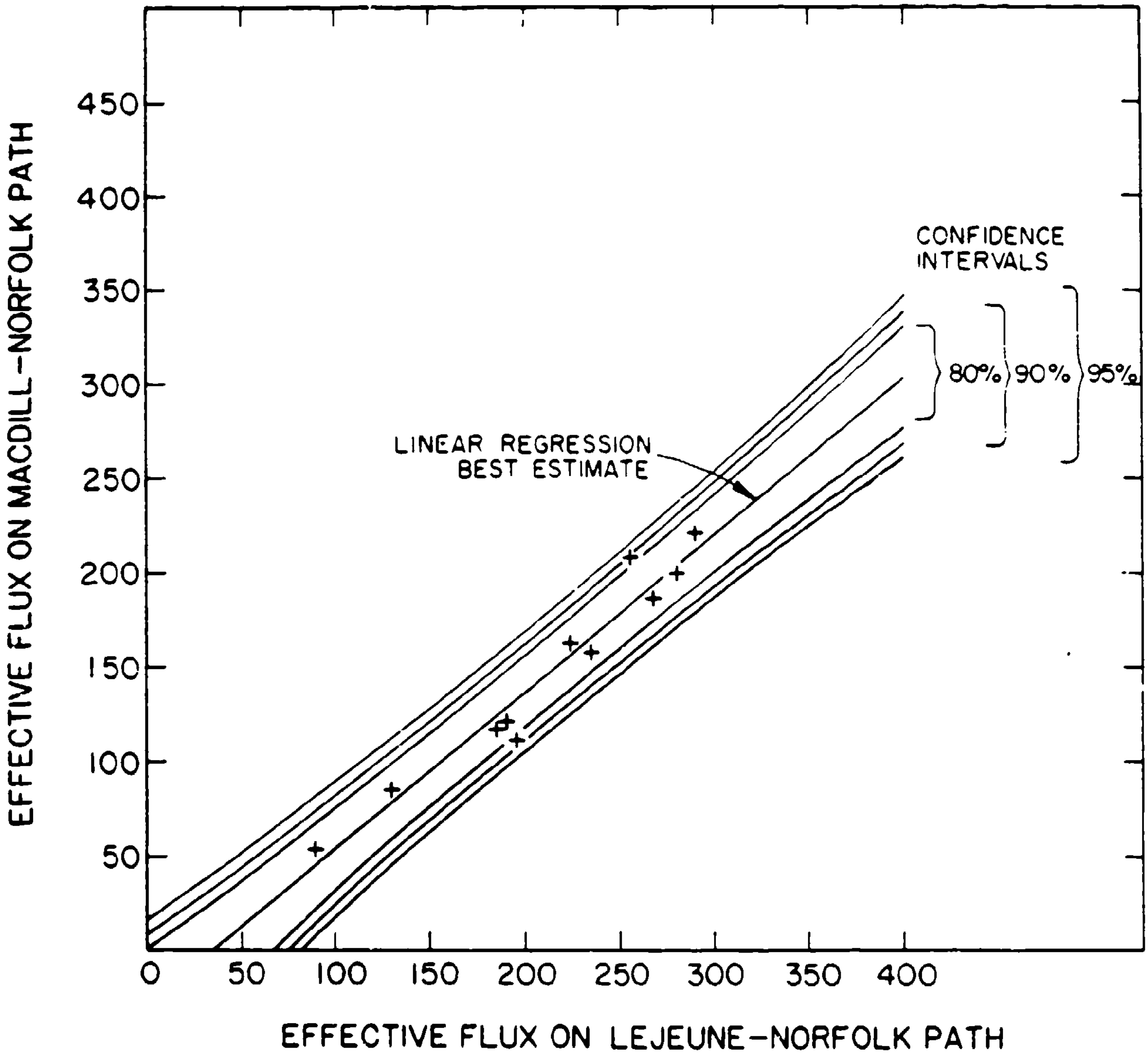

Fig. 9 — Confidence intervals in the prediction of effective flux on the MacDill to Norfolk path in the time interval 0300Z-0400Z, using MINIMUF updated with Lejeune to Norfolk data. Given a measurement of effective flux on the Lejeune to Norfolk path, the best estimate of effective flux on the MacDill to Norfolk path is given by the linear regression line. Three pairs of curves represent the intervals within which the MacDill to Norfolk effective flux may be expected to fall with probabilities of 80, 90, and 95 percent.

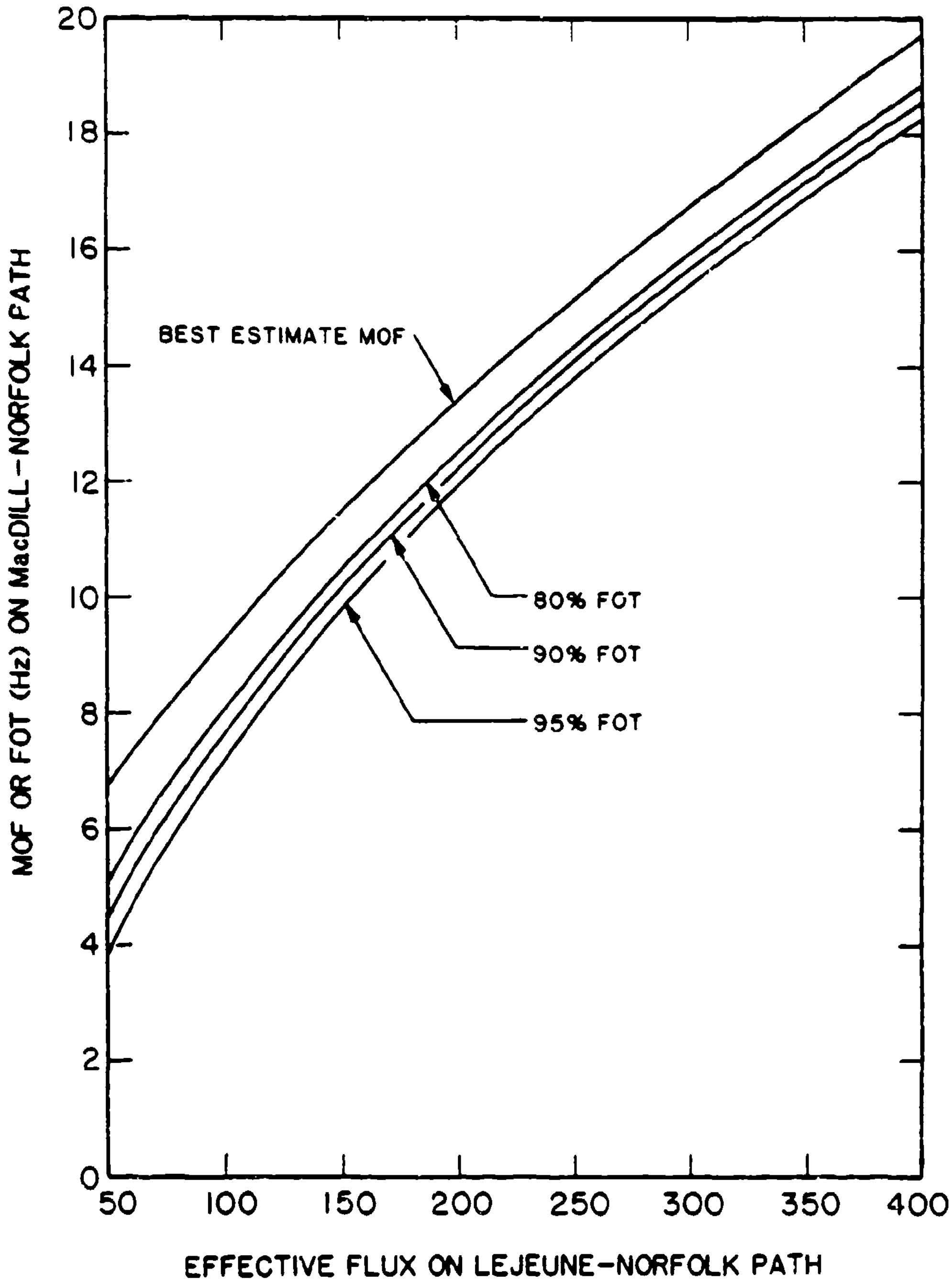

Fig. 10 — Curves for forecasting the Maximum Usable Frequency (MUF) on the MacDill to Norfolk path for the hour 0300Z-0400Z. Given a measurement of effective flux on the Lejeune to Norfolk path, the upper curve gives the best estimate of the MOF on the MacDill to Norfolk path. The other three curves are guides for determining a MUF with a specified probability that this frequency will be at or below the actual MOF. For example, the "80% MUF" is the highest frequency which, with 80% probability, will be at or below the actual MOF.

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